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River-Bed Processes and Contemporary Vertical Movements of the Earth's Crust

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~~STREAMBED~~ PROCESSES AND THE CONTEMPORARY VERTICAL MOVEMENTS OF THE EARTH'S CRUST

D. A. Kozlovskiy

All the conclusions of modern hydrology on the dynamics of riverbeds are founded on the hypothesis that the geological situation in the epoch through which we are living may be considered unchanging. In other words, the view has been adopted that the earth's crust, in out times, is no longer undergoing any substantial reorganization, and that the contemporary rivers are merely smoothing out the tectonic disturbances of epochs long past.

Not so very long ago the view that the quartenary period has been one of tectonic quiet was prevalent among geologists.

During the past two decades ideas have changed radically, and nowadays there are already proponents of the view that not only individual mountain structures or other parts of the terrestrial globe are of recent origin, but that this is also true of the relief of the present epoch as a whole (Lichkov, 1941; Obruchev, 1948; and others).

B. L. Lichkov (1941) has demonstrated in one of his papers that the present epoch, being the immediate continuation of the glacial epoch, is characterized by active relief formation, which has determined the present heights of the mountains and depths of the ocean bottoms.

As. V. A. Obruchev (1948) puts it, "neotectonics completely explains all the peculiarities of the contemporary land relief throughout the whole world."

It must, however, be noted that down to the present moment we still have no entirely convincing method that would allow us to estimate the movements of the earth's crust that are proceeding during the contemporary epoch.

Thus, S.A. Gatuyev (1947) says that "owing to the insignificant scale on which such phenomena (contem orary movements -- D.K.) take place during a short segment of time, they cannot be established by simple observation; and it is possible to note small secular movements leading to a change in the elevation of one point with respect to a neighboring point only hwere there is a standard, permanent hypsometric point or plane of reference (sea level -- D.K.)."

Therefore, when they speak of neotectonics, geologists usually have in mind a fairly prolonged segment of the second half of the Quartenary period.

For instance, N.I. Kikolayev (1947), in characterizing the latest movements, places them in the Holocene, i.e., in Postglacial time or the epoch of Neolithic man.

L. A. Vardanyants (1948), while recognizing that the Quartenay period does not yield precedence to the more ancinet epochs in the scale on which geological processes have unfolded, and considering that "the phases of intensive manifestation of orogenesis, vulcanism, erosion, et. are located in the perspective of time very close to that of the present day," maintains nevertheless that we are living now "in a condition of relatively marked equilibrium, in which erosion connected with relative elevations of its base, appears much more weakly (in the Caucasus -- D.K.)."

The latter conclusion of L. A. Vardanyants does not agree with the results of analysis of the hydrologic data, which compels us on the contrary, to hold that the post-Khvalinsk orogenesis in the Caucasus is not only not dying out, but is still continuing at the present time, possibly even with undiminished intensity. This is confirmed by the stormy erosion activity of rivers and gullies, by earthquakes, landslides, etc. (Gushevaya, 1948, Lamakin, 1948; Shlepnev, 1947.).

No one disputes the influence of tectonics, in the geological apect, on the formation of ~~stream~~riverbeds and valleys. On the contrary, the rivers reflect the tectonics. The antecedent valleys, sea and river terraces, rapids, etc. -- all these factors had their effect on the indices of vertical movement of the lithosphere.

Before taking up the estimation of the vertical movements of the earth's crust by the hydrologic method, and before pointing out their influence on ~~strea~~river-bed processes, we must first dwell upon the theoretical postulates of this method.

It is generally known that every river, in constructing its channel, has a tendency to develop a smoothed longitudinal profile in the form of a smooth curve without sharp breaks.

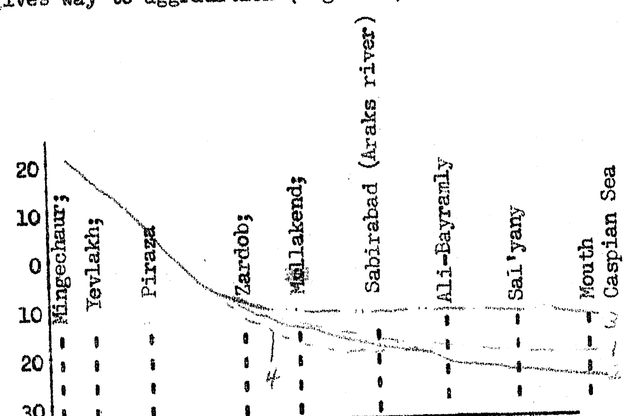
In disturbing the longitudinal profile, the vertical movements couteract the work of the river and force it continually to realign and adjust its bed. Change in the position of grade and base level occurs during these displacements of the earth's crust, and in consequence the river is compelled to carve out the breaks or to fill in by aggradation, the bulges in its longitudinal profile.

What effect has this on the streambed processes of changing the erosion level? Let us take up specific instances.

We find very clear examples of a negative movement in the erosion level, and its action on the formation of a river profile taking place before our very eyes in the basin of the Caspian Sea, the level of which was sharply lowered during the period from 1929 to 1945.

The lowering of the erosion level here is manifested above all in the deepening of the estuary sections of the rivers flowing into the Caspian. This is, in particular, most graphically shown on the lower reaches of the Kura river, where it proved necessary to construct levees to protect the adjoining lands on the edge of the Kura-Araks lowlands only as far as Sal'yan (85 kilometers from the mouth). Downstream of this point, the river has cut so deeply into its deposits that even in catastrophic floods the water does not overflow its banks, and therefore there is no need of levee work on this section.

With the passage of time, the cutting of a river channel may continue along a longitudinal profile which was adapted to a different location of the erosion level. When we compare the longitudinal profiles constructed according to the mean monthly low-water marks of December 1932 and October 1945 (i.e., during periods respectively corresponding to the commencement of the intensive lowering of the level of the Caspian, and to its lowest position), we must establish the fact that it was precisely this drop in the level of the sea, which amounted to 1.79 meters over the 13 years, that produced the reduction of the low-water mark in the river. The progressive erosion of the river channel that accompanies this fall in level gradually becomes weaker with increasing distance upstream, and finally tapers off a short distance above Mollakend, 305 kilometers from the mouth. Upstream of this point erosion already gives way to aggradation (Figure 1).



	Mingechaur	Yevlakh	Piraza	Zardob	Mollakend	Sabirabad	Ali-Bayramly	Sal'yany	Mouth
Low-water mark in December 1932	15.74	9.86	2.59	8.51	13.00	15.98	21.17	24.05	25.62
Low-water mark in October 1945	16.35	9.30	2.33	8.35	13.40	16.65	22.28	25.52	27.41

Slope of stream surface in %	0,147	0,117	0,082	0,041	0,045	0,055	0,046	0,019	
1932/1945	0,149	0,112	0,079	0,046	0,049	0,059	0,052	0,023	0
	600	500	400	300	200	100	0		

Figure 1. Kura River. Change in Longitudinal Profile from 1932 to 1945.

Legend: 1: January 1932. 2: October 1945. 3: Normal profile corresponding to upstream portion. 4: Normal profile corresponding to downstream portion.

Thus as the grade is lowered the corrosion of the channel gradually moves upstream, at the same time diminishing in intensity.

The deep erosion can be followed even better by plotting discharge curves for a number of years on the same chart; in this case usch curves will lie parallel to each other and beneath each other (Polyakov, 1946). As a result of the lowering of the grade, the erosion of the Kura channel can be very distinctly followed from the discharge curves at Sal'yany and Sabirabad, that is, at a distance of 240 kilometers from the mouth (Figure 2). No stream gaging was done at other points along the erosion sector.

The deep deformation of the channel may also be followed by the annual low-water marks at the gaging stations. It must be taken into account that a systematic recession of the low-water marks points to the erosion of the channel at the point in question, and, on the other hand, the regular rise in such marks points to the raising of the river bottom as a result of the accumulation of alluvial deposits at that point. It is true that this method is less accurate than the preceding one, since the annual low-water marks vary to some extent with the discharge, but it still allows the deformation of the channel to be followed at points where no hydrometric work is being done.

When the corrosion of the ~~stream~~ river bed on the lower reaches of the Kura is estimated by this method, the conclusion can be drawn that at Sal'yany (Figure 3) a steady lowering of the channel has been proceeding for a long time, and was particularly intense in 1930.

The opposite process, i.e., the elevation of a river bottom and the consequent upward displacement of the discharge curves or elevation of the low-water marks must obviously await a relative elevation in the grade of the river, which may result either from elevation of the sea or subsidence of the dry land.

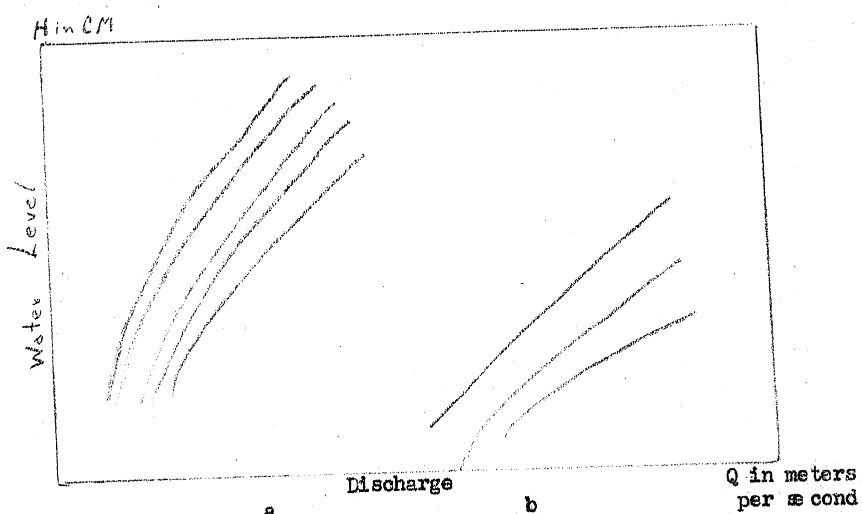


Figure 2. Kura River. Downward displacement of the discharge curves in consequence of the corrasian of the channel brought about by lowering of the grade. a: at Sabirabad; b: at Sal'yany

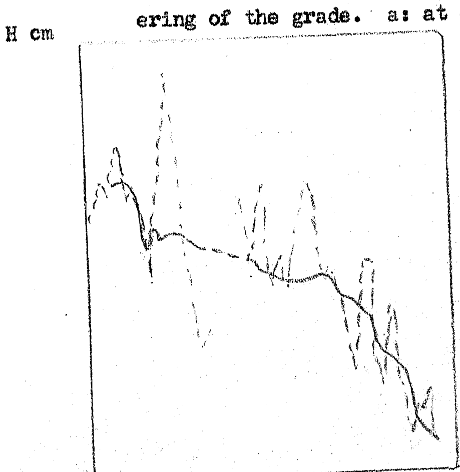


Figure 3. Kura River at Sal'yany. Recession of the annual low-water marks during the period 1900-1945, resulting from channel erosion due to lowering of the grade. Dotted line shows actual position of stream

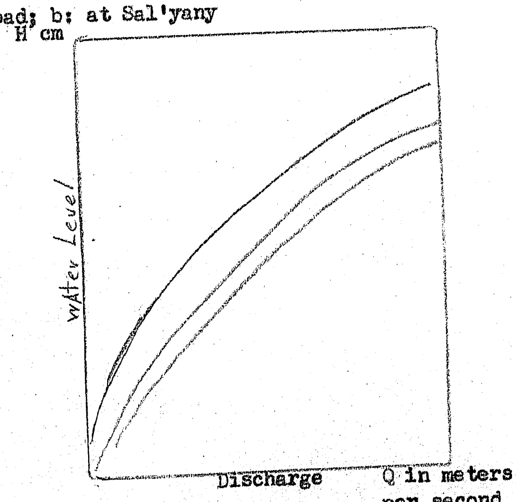


Figure 4. Kuban' River at Krasnodar. Upward displacement of discharge curves resulting from accumulation of alluvium due to relative elevation of the grade

Such a relative elevation of the grade at the present time is going on, for instance, on the Black Sea coast of the Caucasus and the Taman' peninsula, as may be judged from numerous signs noted in the literature (Nikolayev, 1949). The results of repeated precision levelling, indicating subsidence of the shore in the Poti region at the rate of 1 centimeter a year (Shlepnev, 1947); the flooded river mouths (Arkhangel'skiy and Strakhov, 1938; Nikolayev, 1949); the destruction of beaches and buildings located thereon (Adler, Sochi, etc.); intensified development of earth-creeps and landslides, and the subsidence below sea level of the lower strata of the ancient city of Fanagoriya on the Taman' peninsula (Blavatskiy, 1940); the widespread distribution of pozzuoli (Herts, 1870), etc. -- all these are signs that leave no doubt of the continued subsidence of the foot-hill zone.

A relative elevation of the river grade results from the subsidence of the coastal belt. The rivers that flow into the sea here react to this by intensive accumulation of alluvium in their lower reaches.

The lower Kuban' is also very distinctly aggrading its bed and striving to occupy the dominant position on the surrounding plain. In view of this it became necessary to carry out embankment works on the channel of the Kuban' and to increase the height of the levees gradually, from year to year (Shchukin, op. cit., 1933, p. 115).

The relative elevation of the grade of the Kuban' River is marked by the accumulation of alluvium as far as Krasnodar, at which point the discharge curve tends to rise (Figure 4).

It seems to us that these reasons furnish sufficient basis for considering that a change in the grade of a river brings about a realignment of the longitudinal profile, and as a sign of this, a displacement of the discharge-curves or low-water marks in the corresponding direction. We have been brought to this conclusion by consideration of the estuary sectors of rivers, in which grade erosion level and sea level are identical. The relative change in its position is obvious, both from the hydrometric observations that determine its position (Caspian) or from the entirely convincing signs of subsidence of the dry lands (coast of the Black Sea, Taman').

If there is no doubt as to this thesis, then it must also be agreed that the converse law is similarly valid. In other words, it must be recognized that every more or less persistent shift in the discharge curves, in either direction, or other hydrological indications of readjustment in the depth of a river channel should serve as an index of change in the erosion level.

This deduction serves as the basis for the further conclusion as to the change not only in the final erosion level, but also in the local upstream erosion levels, located far inland. The displacement of the latter, in the overwhelming majority of cases, should be attributed to vertical movements of the earth's crust and much more rarely to other reasons (activity of man, corrosion of banks, etc.)

Numerous examples of persistent erosion and accumulative activity, in depth, by rivers, may be found in the Caucasus, where vertical movements of the earth's crust are taking place during the contemporary epoch.

Most rivers of the Caucasus flow in their upper reaches through longitudinal valleys along the Main Range. They then change direction sharply, and in their subsequent course carve deep transverse valleys through the side chains, which may serve as evidence of the more recent origin of these chains. In their lower reaches the rivers emouch upon plains built up of alluvial deposits, and some of them flow into the sea, forming alluvial fans which are inundated by the waters of the Black Sea.

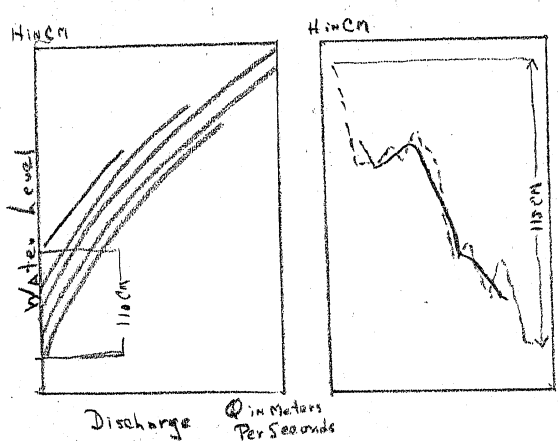


Figure 5. Mzymta River in the Akh-Tsu [Ak-su] Gorge. Downward displacement in the discharge curves a and the low-water mark b.

The river Mzymta, which flows into the Black Sea at Adler, is typical in this respect. In its upper reaches it has a longitudinal valley running between the Main Range and the parallel Achishko-Aibeg range. At the village of Krasnaya Polyana the river turns abruptly towards the southwest; its valley cutting successively through three folds running parallel to the Main Range, takes a transverse (antecedent) direction.

These side chains at the present time are rapidly being carved through by the river, which is obviously an indication that the development of the river still continues.

Observations in the Akh-Tsu gorge show that the range is now being carved away at an average speed of 5.5 centimeters per year (Figure 5). Unfortunately there have been no parallel observations on the adjacent sectors, so that the rate of alluvial accumulation, which would have allowed estimation of the total rate of elevation of the range, cannot be estimated. It is possible, nevertheless, to consider that this rate is probably not less than 5.5 centimeters per year, since the rate of erosion of the channel is the lower limit of the rate of elevation of the range.

The observations in the Akh-Tsu gorge are also interesting because they permit estimation of the rate of erosion of the rock being carved away. In this case we have to do with dense siliceous limestones which, according to M. M. Protod'yakonov (cf. Savarenskiy, op. cit., 1939, p. 26), can be classed among rocks of Category III, with a coefficient of strength of 10.

We find no less interesting a case of realignment of the longitudinal profile of a river in connection with vertical movements: the Kura River, which at Minchegaur village cuts through the Boz-Dag range, composed of a base of Apsheronic rocks, covered by deposits of Bakinsk age (Vardanyants, 1948).

Here the river continues in its constricted valley with steep banks; the channel of the river is made up of rather friable sandstones, to which thin intercalcations of limestone lend a certain firmness .

The Kura debouches from the gorge onto the Kura-Araks lowlands. The latter is an extensive lowland area between the Bol'shoy and Malyy Kavkaz, and its subsidence continues down to the present day (Shlepnev, 1947). At the same time, apparently, the Boz-Dag range, which originated at the close of the Bakinsk stage, continues to rise (Vardanyants, 1948; Grossgeym, 1948).

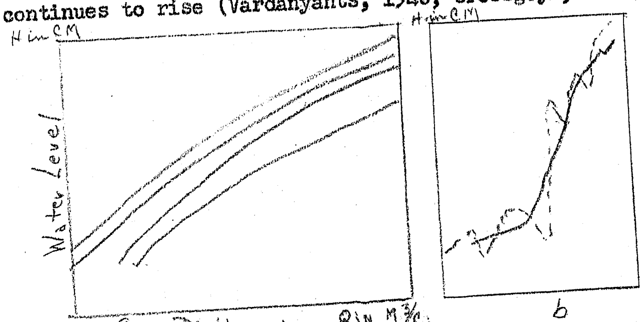


Figure 6. Kura River at Michegaur. Upward displacement of discharge curves in a and low-water marks in b resulting from accumulation of alluvium caused by the mutual relative displacement of the Boz-Dag range and the Kura-Araks lowlands.

The elevation of the Boz-Dag range relative to the Kura-Araks lowlands is fixed by the river, which energetically deposits alluvium at its exit from the gorge, thus restoring its profile, continually disturbed by vertical movements. The rise in the channel bottom at Minchegaur, noted when the observations first started in 1912, continues at a mean annual rate of 6.3 centimeters (Figure 6), and consequently, the simultaneous uplift of the range relative to the subsiding plain may be estimated at this figure (as a minimum), neglecting for the purpose of this calculation the rate at which the rising range is being carved through, which rate may possibly be no less than this, but at any rate is still unknown to us. Downstream, the rate of alluvial deposition slackens. Thus, it amounts at Yevlakh to 4.4 centimeters a year, at Zardob to 2.9 centimeters, and finally, a short distance upstream from Mollakend, as we have already observed, aggradation of the bed gives way to degradation. The reduction in the rate of alluvial deposit, as well as the replacement of accumulation by erosion, should doubtless be attributed to the recession in the erosion level, i.e., the level of the Caspian Sea.

To illustrate how a river behaves when a certain sector of its valley subsides, we shall now take up the formation of the bed of the Kuban' River.

In its middle and lower reaches, the present Kuban' River continues to flow in the channel along the synclinal fold which, according to Vardanyants (1948), originated in the Khvalinsk stage, and has continued its subsidence down to modern times.

The subsidence of the valley is responsible for the relative uplift of the erosion level, in consequence of which, as has been indicated above, alluvial accumulation occurs in this sector.

The left-bank tributaries, like the upper Kuban', on the other hand, which are subject to the influence of a subsiding erosion level, (which the middle Kuban' itself favors), erode their beds in the estuary sectors. The effect of the erosive and accumulative work of the rivers is here apparently to intensify the uplift of the Central Caucasus. The erosion of the stream beds resulting from the subsidence of the Kuban' syncline is particularly intense and systematic on the rivers Il', Khabl', and others. In the Il', a displacement of the discharge curves at the average rate of 10 centimeters a year has been noted since hydrometric work on this river first started in 1924 (Polyakov, 1946).

It must be borne in mind that when the vertical movements are being estimated by the hydrological method, the direction of formation of the longitudinal river profile must be followed all the way down to the lower erosion level. Only on this condition can a conclusion be formulated as to the general direction of these movements. Observations at separated points give the direction of shift relative to the adjoining sectors, while the general motion of the territory as a whole may be at a different rate and even be in opposed sense. On the basis of what has been here set forth, we are in a position to speak of the general (or resultant) direction of motion, since the longitudinal profiles of the rivers we have studied have been followed through from the sector characterized down to the mouth.

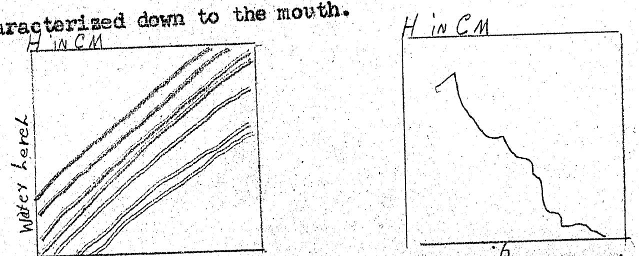


Figure 7. Il' - Il'skaya River. Downward displacement of the discharge curves a and the mean monthly marks b in consequence of

erosion resulting from recession of the local erosion level (Kuban' Depression).

The literature contains numerous indications of recent movements of the earth's crust, which are fixed by the rivers, and only the lack of hydrometric data prevented confirmation, in these cases, of the necessity for terming these movements literally contemporary. Thus, S. A. Gatuyev (1947) gives a description of the contemporary movements noted at the two opposite ends (western and eastern) of the Terek range.

In the former case the Terek range is enveloped by the Terek River, which carving through the upliftіng ridge, uncovers volcanic tuff in its bed. Upstream and downstream from this point, gravel and sands are deposited along its course. The thickness of these deposits has been shown by a boring to be over 70 meters (the bore—hole did not reach the bottom of the gravel layer). At the eastern end of the Terek range, it is pierced by the Sunzha River, which uncovers Sarmatian clays as it cuts through the range. These clays are not covered by alluvium, but upstream and downstream from this point the river bed is filled with pebbles.

We find a description of the whole system of young antecedent valleys on the south slope of the Bol'shoy Kavkaz and the north slope of the Malyy Kavkaz in the paper of V. A. Grossgeym (1948). What are termed the "Padarsk window" are distinguished among them by their effects. They are formed by the Gerdyman-Chay River carving through the uprising Adzhinoursk highlands.

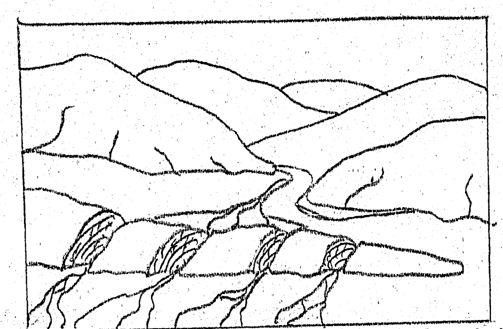


Figure 8. Gerdyman-Chay River carving through the rising ridge (Padarsk windows). (After V. A. Grossgeym).

According to the unanimous opinion among geologists, the formation of the Caucasus is continuing today. L. A. Vardanyants (1948) considers that "at the end of the Pliocene, the Caucasus was a levelled, weakly dissected land... at the edges of which the highest portions hardly rose 1.5 kilometers above the level of the ancient Caspian." (op.cit., p.31). Thus, during the Quaternary period, i.e., during the space of 500,000 to 700,000 years, the Caucasus was uplifted along its axial line by not less than 2.5 - 3.0 kilometers. Taking due account of the fact that throughout the Quaternary period the orogenic phases alternated with phases of relative quiet, L. A. Vardanyants (op.cit.) considers that the uplift of the Central Caucasus may have attained an annual rate measured in tens of centimeters at certain moments of greater stress, while mean annual rates of formation during the orogenic phases were around 2.5 - 5 centimeters.

In the light of these assertions, the values obtained by us, using hydrometric data, for the velocities of contemporary vertical movements, reaching 5 - 10 centimeters a year, cannot be considered unreasonable. On the contrary, they confirm that the Caucasus, even today, still continues to live through an orogenic phase no less intense than in the preceding epoch, and very possibly, constituting its continuation.

Incipient tectonic movements, which are reflected in the erosive and accumulative work of the rivers, are noted in other mountainous regions as well. B. V. Polyakov (1946) points out that in the Carpathian mountains, at Byala-Dunechek, a recession of the river bed of over 2 meters has occurred during 20 years, giving a mean rate of 10 centimeters a year.

Based on his own observations and those of other investigations (cf. Lichkov, 1941), P. S. Makeyev reaches the conclusion that an energetic process of deepening of the river channels is proceeding in Central Asia at the present time, in consequence of which the flood plains, still formed in historic times, are gradually being transformed into second terraces.

The very recent and literally contemporary vertical movements are not confined to the regions of recently formed mountains, but are noted as well on the platforms, concerning the present movements of which no entirely definitve statements can yet be made.

G. V. Obediyentova has established, by her geomorphological study of South Meshchera, that in the valley of the Oka "the contemporary river alluvium is gradually extending the area of its distribution. This is taking place as a result of the rise in the level of the rivers and the overflowing of their banks, and is accompanied by an increase in the area of swamps" (1948, op.cit., pp. 188).

In drawing her conclusions, she poses the question: "How are we to explain this rise in the river level and this intensification in alluvial accumulation on its flood plain in this region? It is rather difficult to answer this question definitely enough; but what is most probable is that the intensification of alluvial accumulation is taking place in consequence of a slow epeirogenic subsidence of the region" (op.cit., pp. 188-189).

V. V. Lamakin (1948) in proving the existence of recent movements in the valley of the middle Pechora, starts out from geomorphological observations. He bases his conclusion on the deformation of terraces, on the changes in the hydrographic system since the time of maximum glaciation, and finally, on the dynamic peculiarities of the contemporary valley.

In investigating the erosive and accumulative work of the river along its valley, he notes the sectors that are undergoing uplift or subsidence, and in the intervals separating such sectors, those sectors of the valley where the streambed is in a condition of dynamic equilibrium. This latter method used by Lamakin for his demonstration, is substantially identical with our own, with only the difference that he gives a qualitative appraisal of the phenomenon, while we, on the basis of hydromteric data, establish the quantitative side of the process.

Besides completely confirming our own deductions, Lamakin's investigations are also interesting because they establish the entirely palpable movements that are taking place at present on the northestern edge of the Russian platform, about the mobility of which opinions differ.

There is, however, one group of scientists who express themselves on this subject with a considerable degree of definiteness. Thus N. I. Nikolayev (1947) says that "extremely recent oscillating movements are everywhere observed over the entire territory of the Russian platform, and in the adjoining regions of other structural elements of the earth's crust. And there are no places where such movements do not exist."

All the examples we have presented show how sensitively the rivers react to tectonic disturbances.

By virtue of the mobility of its stream of water, every river must be considered as a single system, the separate sectors of which depend on the condition of the river as a whole, and conversely: every change in its separate sectors produces a readjustment in the channel at least in the neighboring sectors, if not in the whole river. On the other hand, river systems of great length traverse various geomorphological zones in their courses, and the vertical motions in these zones differ in direction and intensity. We should therefore expect the longitudinal profile of a river to be a good indicator of contemporary orogenic and epeirogenic processes.

A study of the character of the longitudinal profiles of rivers fully confirms this expectation.

The work of S. V. Grigor'yev (1946) is very valuable in this connection. In estimating the energy resources of small rivers, this author has classified about 800 rivers of the European and Asiatic parts of the USSR.

In spite of all the variation in the character of the curves, he reaches the conclusion that all of them may be classified into three basic types, of which the first has a curved longitudinal profile bulging downwards, the second has a linear profile, and the third a curved profile bulging upwards (Figure 9).

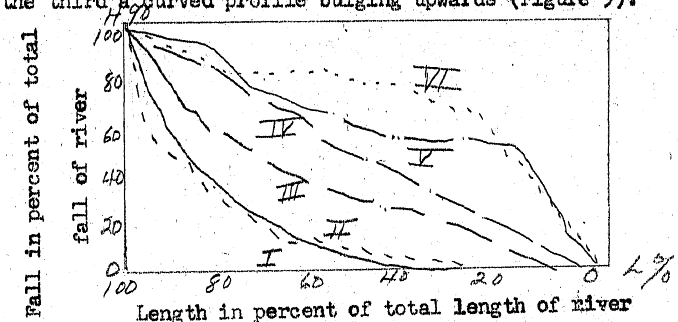


Figure 9. Typical curves of longitudinal river profiles.

1st type: concave (I: Rioni; II: Sochinka);

2nd type: linear (III: Kama; IV: Tal'ka -- Dnepr Basin);

3rd type: convex (V: Taparovan - Transcaucasia; VI: Lososinka - Lake Onega basin).

It must be recognized that the idea of classifying river profiles by types in itself is of great interest, and in conjunction with the regional classification of rivers by their longitudinal profiles, furnishes rich material for the evaluation of the disturbances that occur during vertical movements of the lithosphere. At the same time the reservation must be made that the distribution of river profiles by types can be made only conventionally, since it would be very hard to find examples of these types in their pure state. Longitudinal profiles, as a rule, have a stepped shape and are often combinations of different types (for instance, the Dnepr, Figure 10).

If account is taken of the actual rate at which a river excavates its channel, the extraordinary variety in the character of the longitudinal river profiles may be explained by the vertical movements taking place in our own times. It is, of course, impossible to believe that, in the absence of such movements, the rivers would not have developed smooth, even profiles during the course of tens and hundreds of thousands of years.

As we have already remarked, the rate at which even solid rock is carved through may reach a few centimeters a year. And even if the rate of rock excavation is lower than this for the progress of rivers in the plains, we must still agree that the overfalls are still being carved out, even here. These overfalls could not last for centuries if they were not reinforced by contemporary vertical types is very significant.

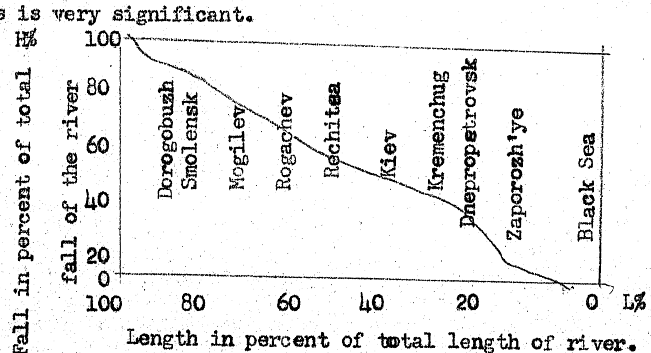


Figure 10. The Longitudinal profile of the Dnepr.

The concave type of longitudinal profile curve proves to be characteristic for the Caucasus -- a young mountain system, the formation of which is still continuing at the present time. There is no doubt whatever that there can be no profile of equilibrium while the relief is still being formed. And what was erroneously taken by S. V. Grigor'yev (1946) for a straightened profile is in reality only an apparent or "quasinormal" profile.

Most rivers in the Caucasus clearly display a "quasinormal" profile, especially the largest rivers: the Kura, Rion, Terek, Malka, Sunzha, Kuma, etc. On the Black Sea coast, the Mzymta, Shakhe, Sochinka and many others have this type of profile (Figure 11). In this list we encounter just those rivers that were used as examples to demonstrate the influence of endogenous forces on profile formation.

As the first (concave) type of profile is most characteristic for the Caucasus, so concludes S. V. Grigor'yev (1946), is the third (convex) type characteristic for the Kola Peninsula and Karelia, where uplift is proceeding in the contemporary period. The rivers here are short and flow into the seas and lakes. As the region undergoes general uplift, the rivers erode their tidal sectors most intensely of all, and develop a convex profile, with maximum slope in the lower course (Figure 12). The stepped formation (existence of many rapids) is characteristic of this type of profile, and should doubtless be attributed to the uneven uplift of the various parts of the region, and to the disjunctive dislocations connected with it. The large number of lakes that is so characteristic of the Kola Peninsula and Karelia is, apparently, intimately connected with contemporary vertical movements and originates in the backing up of rivers and pond formation as well as in consequence of glacial action.

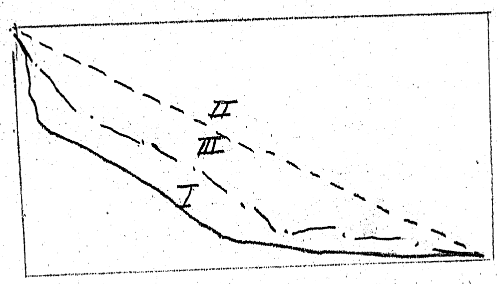


Figure 11. Longitudinal Profiles of Rivers in the Caucasus

I. Mzymta (Black Sea Region); II. Gyurgen-Chay (Azerbaydzhan); III. Ullu-Kam (Kuban' basin).

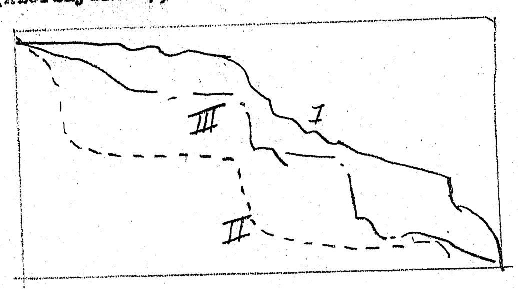


Figure 12. Longitudinal Profiles of Rivers in the Baltic Shield

I. Kem'; II. Segezha; III. Vyg.

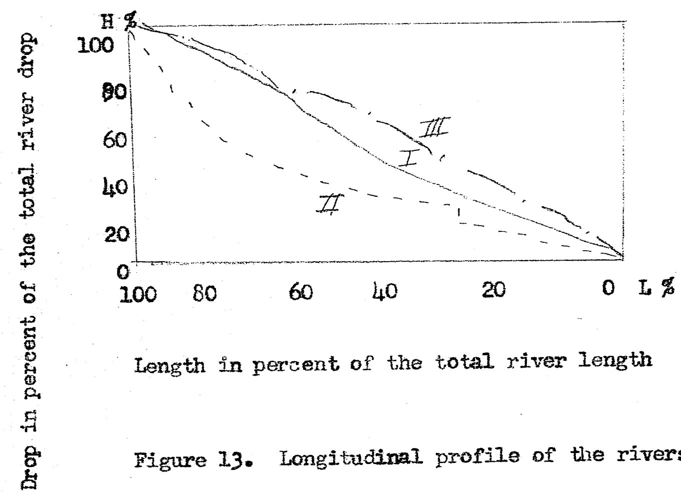
The linear profile (second type) is inherent in the rivers of level regions and is prevalent among most of the small rivers of the European and Asiatic parts of the USSR. (Figure 13). This type of profile, like the other two, bears the traces of contemporary movements, which are primarily manifested in its stepped structures. To us this seems to be indicated not only by the considerations above set forth, but also by the intensified gullying activity (increase in the energy of the relief) which is manifested in the central belt of the European part of the USSR from the Carpathians to the Urals. The Central Russian Highlands, in particular, stand out in their pronounced erosive relief, which is dissected to such an extent by a system of valleys and ravines that, in places, the width of watersheds does not exceed 1.5 - 2 kilometers. (Guzhevaya, 1948).

The maps showing numerous ravines, presented by A. F. Guzhevaya (op.cit.), are confirmed by S. S. Sobolev's map of 1938 showing the depths of the local erosion levels, which furnishes reason for considering the intensification of the energy of relief formation as the basic factor that determines the development of ravines.

Sobolev (1938) considers that "the contemporary cycle of deep erosion in the river valleys is closely connected with the contemporary cycle of deep erosion in the ravines and gullies (erosion of the bottoms and to some extent of the sides as well), since the rivers form the local erosion levels of the ravine-gully systems." (op.cit., p. 1133). N.I. Nikolayev, in considering the geomorphology of the Volga highlands, points out the same thing. He considers that "the considerable development of the ravine-gully system is characteristic of this region. On the right bank of the Volga the ravines and gullies are very deep, ramified and highly eroded. In many places ravines have been formed at the bottom of ancient gorges, which points to the recent nature of the movements" (op.cit., p. 184).

Under what conditions is one profile or the other developed?

According to Airy's law, the coarseness of the alluvium is



Length in percent of the total river length

Figure 13. Longitudinal profile of the rivers of the Russian Plain.

I. Tur'ya (the Pripyat' basin),

II. Bulavin (the Don basin),

III. Tvertsa (the Volga basin),

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directly proportional to the square of the velocity, i.e., $v^2 = ad$, where v is the stream velocity, d is the diameter of the alluvium, and a the coefficient of proportionality.

On the other hand by the Chezy-Manning formula, $v = c\sqrt{HI}$, or $v^2 = c^2 HI$, where v is the stream velocity, H the mean depth of the stream, I is the slope of the surface of the river for the given course, and c is the coefficient given by Manning and equal to $\frac{H^{1/6}}{n}$ where n is the roughness factor.

On equating the right-hand sides of the first two equations, and substituting Manning's value for c, we obtain

$$I = an^2 \frac{d}{H^{4/3}} = K \frac{d}{H^{1.33}}$$

Thus we see that the slope of the river surface increases as the thickness of the alluvium increases.

This is precisely the situation that is observed in nature. In mountainous regions, where coarse debris enters the upstream reaches of the rivers, it is not transported further until such time as the current acquires the necessary velocity, and consequently the corresponding slope. Downstream along the river, as the detritus becomes more and more abraded and worn down, the coarseness of the alluvial deposits diminishes and accordingly the slope of the stream also diminishes. In the lower course, where the river bottom is composed of fine alluvium, the slope of the stream diminishes even more and falls to a negligible value, while the depth of the stream increases.

With flatland rivers the situation is different. Here, throughout the entire course of the river, the bed is composed of material varying little in its coarseness, especially where the tributaries carry supplementary loads of coarse material into the main stream. For this reason rivers that flow through plains have almost linear longitudinal profiles.

Thus when we examine the longitudinal profiles of rivers in different geographical regions, we see that all of them bear, in greater or lesser degree, the traces of recent, contemporary movements of the earth's crust.

If this is the case, then on coordinating the bendings in the longitudinal profiles of the rivers with the geomorphological, geological and hydrological signs of very recent tectonic processes, we are in a position to draw a more complete chart of the contemporary vertical movements. Such charts should undoubtedly be of great practical value, for they can be of great help to the hydrologist in studying the work of the rivers in forming their beds.

It is of course impossible to admit that the readjustment of the channel in depth and the lateral readjustment of the channel proceed independently of each other. There is no doubt that the work of the river in one direction is intimately connected with that in the other direction; and it seems to us that both these processes are component elements of the general process of developing the longitudinal profile of the river. When we study the formation of the river channel in connection with changes in the lower erosion level, we are led to this conclusion. To prove the thesis we have advanced, we turn once more to the Kura, whose estuary portion is being formed before our very eyes as the level of the Caspian Sea recedes.

As may be seen from contemporary maps, the main channel of the Kura in its delta section has almost a linear course, which is maintained in the presence of a stable erosion level. The banks of the river here are subject to no appreciable erosion whatever, in spite of the high velocities of the current, especially on the passage of a flood wave, when an abatement curve of the water surface originates at the mouth of the river, producing considerably greater stream slopes than on the upstream sectors. The high velocities of the stream result in erosion of the channel bottom, with resulting depths of 10 - 12 meters, but there is no lateral erosion of the channel, and consequently the stream has no tendency to meander in this sector.

On the following of the channel of the river upstream, we become convinced that the meandering of the river is gradually increasing. Slight bends in the channel appear at first, but as the distance from the mouth increases, the bending also increases, and then become distinct meanders, the curvature of which increases as we pass upstream.

The increase in the meander coefficient from the mouth to the upper reaches keeps pace with the increasing slope of the stream in the same direction (see table below).

In investigating the causes for the meandering of the river, we were limited to the sector of the Kura lying within the limits of the Kura-Araks lowlands, for here the river has a relatively youthful channel, formed under similar circumstances from the beginning of the post-Khvalinsk times down to the present, accompanied by gradual recession of the erosion level (with, it is true, some breaks in that recession), and the channel is consequently of uniform genesis. Therefore when we go more into detail as to how the channel changes in any sector segment of this course, we shall obviously have sufficient basis for generalizing our conclusions for all the sectors of the river, taking into consideration at the same time that the processes taking place on the gives segment presumably continue their development in the same direction on the segments located further upstream as well

CHANGES IN THE SINUOSITY [MEANDERING] OF THE KURA RIVER AS RELATED TO THE SLOPE OF THE RIVER

Number of river sector counting upstream from the mouth	Meander Coefficient	Slope of the water surface
1	1.03	0.0000095
2	1.09	0.000024
3	1.50	0.000035
4	1.68	0.000047
5	1.52	0.000057
6	1.71	0.000036
7	1.90	0.000044
8	2.32	0.000083
9	2.06	0.000111

Let us examine, as an example, the relatively youthful sector of the Kura (in the region of the southeast bank), concerning the evolution of which we possess sufficiently reliable information.

Some 70 - 80 years ago, this sector belonged to the delta course of the river and was divided into a number of tributaries. With the recession of the shore line of the sea, a main channel of the river was formed, and the tributaries gradually ceased to exist. The channel being formed in a southeasterly direction assumed a linear form and remained so for over 50 years, without undergoing appreciable erosion, as is shown by various shore installations that still remain.

The marked recession of the level of the Caspian Sea in the 30's drastically changed the existing situation. As the delta of the river moved forward into the sea, the length of the river increased, but its fall over this sector increased immeasurably more, as a result of which the slope of the stream surface also increased. This caused a deepening of the channel, and at the same time the river began to erode its banks as well. During a relatively short period, on the sector of the Kura experimental fish hatchery, the river carved out about 100 meters of the shore belt.

The fish hatcher was built in 1935, near the Kura, for there were no doubts as to the stability of its banks. But shortly after the construction of this station, erosion of the banks commenced, threatening a number of the station installations with col lapse. As time passed, the lateral erosion grew more intense, and many installations, even including some located at considerable distances from the bank, were destroyed.

We see from this example how a stable and linear channel, that had not undergone appreciable lateral erosion even at high stream velocity, commenced, with a fall in the erosion level and an increase in the stream slope, to develop meanders. And as we follow the channel upstream, we see that the further increase in the stream slope, intensifying this process, leads ultimately to the formation of pronounced meanders.

When we study the dynamics of the Kura River channel within the limits of the Kura-Araks lowlands, we must take into consideration the fact that the channel-forming processes proceed here under the influence of two opposing factors. On the one hand the influence of the falling erosion level manifests itself, resulting in the disappearance of the delta, in regressive erosion, in increase of the stream slope and in development of meanders; while on the other hand, as has been noted above, a general subsidence of the plain takes place, which attenuates the slope of the stream, and causes alluvial accumulation, and development of the delta at the river mouth. These two directly opposed influences interact, and the direction to be taken by the channel formation depends on which side wins. The influence of the fall in the level of the Caspian is more strongly expressed in the lower course, at the points where strong erosion in depth occurs. From the place where alluvial accumulation commences, the endogenous forces which are responsible for the general subsidence of the plain are obviously taking the upper hand.

With a rise in the level of the sea, or even if that level holds unchanged, deep erosion ceases; alluvium is deposited in the estuary region of the river, and the more intensely, the higher the rate of epeirogenic subsidence of the plain. With this, favorable conditions for the development of the delta are created anew.

We have an opportunity of following the action of the rising erosion level on the streambed processes in the middle and the lower course of the Kuban' River, where the general subsidence of the valley is producing alluvial accumulation and a tendency of the river to rectify its channel so as to increase the slope of the stream.

It has been established by repeated surveys in 1911 - 1912 and again in 1928 - 1929, that the Kuban' River was shortened by 10 kilometers on the sector from Ust' -Labinskaya station to Krasnodar, by 5.1 kilometers from the Afips River to Varenikovskaya station, and by 2 kilometers from Varenikovskaya station to the mouth. Thus in 17 years the Kuban' was shortened by 17.1 kilometers, or 5.1 percent of its length, giving an mean annual shortening of 0.3 percent.

These examples convince us that deep (longitudinal) and lateral readjustments of the channel proceed simultaneously. This conclusion of ours does not contradict the view of M. A. Velikanov (1946, op.cit., p. 432) to the effect that "if in the process of developing its channel the stream does not attain the slope that creates conditions of dynamic equilibrium for it, the shape of that channel will be subjected to constant changes and disturbances."

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The internal forces of the earth, in disturbing the longitudinal profile of a river and thereby also disturbing the conditions of dynamic equilibrium, compel the stream to readjust its channel. The correction of the stream slope proceeds by way of both deep and lateral (of course, where permitted by the geological structure of the channel) erosive and accumulative work. The development of meanders or the rectification of the channel lead to changes in the length of the river, while changes in the slope of the stream are followed by realignment of the cross section of the river, inasmuch as the size of the latter, being directly proportional to the discharge, is inversely proportional to the square root of the stream slope.

If L is the length of the river along the vallye, and l the length of the river along the channel, the coefficient of meander is defined as $\gamma = \frac{l}{L}$, or $l = \gamma L$.

But the slope of the stream is equal to $I = \frac{\Delta h}{l}$, and therefore, $I = \frac{\Delta h}{\gamma l}$

Substituting this expression in equation (1) obtained by us above, we have:

$$\Delta h = KLd \frac{\gamma}{H^{1.33}}$$

When we take into consideration the fact that L, the length of the river along the valley, is a constant quantity, we are enabled to say that, with the lowering of the erosion level and the increase of the fall over a given sector, the bed of the river will be reorganized by way of an increase in the coarseness of the material composing it; and together with this an increase in the meandering and a decrease in the depth must also be expected. On the other hand, with an uplift in the erosion level and a reduction in the slope of the stream, finer material will be accumulated in the bed of the river; and the depth should also increase, while the river will tend to rectify its channel and eliminate its meandering.

This process should continue until dynamic equilibrium is established. But since the internal forces of the earth are acting all the time, while the stream is uninterruptedly changing its discharge, there is a ceaseless conflict between stream and channel. M. A. Velikanov (1947, op. cit., p 302) says that "there exists an interaction between channel and stream; the channel governs the stream and the stream governs the channel. The degree of stability of the channel depends on which of these actions proves to be stronger than the other."

In our treatment, this though takes on the following tinge. Under the influence of the endogenous forces, the channel, as we see it, becomes an active agent, which in disturbing the dynamic equilibrium of the stream, excites a reaction in the latter to every change in the bed of the river. When the slope of the stream increases under the influence of the internal forces of the earth, the stream acts to oppose that increase. And together with its deep erosive and accumulative work it also develops meanders, in consequence of which the length of the river increases and its slope diminishes. On the other hand, when the slope of the river diminishes under the action of the same internal forces, the river accumulates alluvium, and this results in raising the low-water marks of the river and facilitates the rectification of the meanders during periods of flood, after which the length of the river contracts, while its slope increases.

In most cases deep erosion is more active than lateral erosion, since the stream has greater energy in this direction. It is usually sufficient, even in intermittent streams, to carve through solid rock. Under these conditions there is practically no lateral erosion. It is for this reason that, in mountainous regions, where a river passes through rocky gorges, the development of the longitudinal profile proceeds on the whole by way of deep erosion, and only after entering a wide valley or plain, made up of rocks which, at the existing stream velocities, are subject to lateral corrasion, does the river get enough room to correct its slope by meandering.

In connection with the propositions above set forth, it seems to us that the geomorphological riddle formulated by I. S. Shchukin is cleared up. In his book, he puts it as follows: (op.cit., 1933, p 125): "...the question is obscure as to why, when periods of erosion recur, each new valley is narrower than its predecessor. It may, however, be thought that this is by no means a general rule. In cases where the new valley proves to be as wide as its predecessor, or wider than it, the bottom of the latter is destroyed, leaving no trace behind, and not a single terrace can be formed. On the contrary, a terrace is formed in cases where the new valley is narrower than the old one."

The answers to these questions are apparently to be sought in the stream-surface slopes that result when a river cuts through in successive cycles of erosion.

If the cutting through led to a stream-surface slope steeper than that in the previous cycle of erosion, then the river, in reducing its slope by meandering, was enabled to destroy without trace the terraces of the former level; but if, on the contrary, the cutting led to a flattening of the slope, then the river, in reducing its meandering, left in existence the terraces along the sides of the valley.

Our task has been a modest one -- to show all the importance of taking stock of the contemporary vertical movements of the earth's crust in working out questions concerned with river conditions.

We trust that this article will prove a stimulus for the reexamination of certain views that have taken root in hydrology, and which must be recognized, in connection with recent achievements of geomorphology and geology, as failing to conform to the current level of knowledge.

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